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A Detailed Examination of the LBL Infiltration Model Using the Mobile Infiltration Test Unit

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ABSTRACT

The LBL infiltration model is a simplified method for combining weather information with air tightness to calculate residential air infiltration. In this report, we compare infiltration-model predictions with data collected by our Mobile Infiltration Test Unit (MITU), a full-scale test structure that gathers detailed weather and infiltration measurements. To probe for sources of prediction errors, we examine four simplifying assumptions made in the LBL infiltration model: 1) that the flow through the cracks in the building shell can be approximated by orifice flow, 2) that wind-induced and stack-induced infiltration can be added in quadrature, 3) that wind-induced infiltration can be represented by averaging the values for three typical aspect ratios, and 4) that wind-induced infiltration can be represented by averaging the values for all wind directions. We make comparisons with measured data to examine these effects qualitatively, and use detailed computer simulations of infiltration in MITU to quantify each effect. The effects of each assumption are represented by the bias and scatter. (The bias is the average error; the scatter is a measure of the ability of a model to track short-term fluctuations in infiltration rate.) We show that the orifice-flow assumption causes an 8% bias and a scatter of 20%, and that the quadrature assumption causes consistent overprediction (bias = 12%, scatter = 6%). For MITU, averaging over aspect ratio causes some overprediction (bias = 11%, scatter = 14%). Although it reduces the ability of the model to track infiltration (scatter = 19%), averaging over wind direction has little effect on the mean infiltration rate (bias=0). When compared to measured data, the LBL model has a bias of 10% and scatter of 28%.

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INTRODUCTION

The predictive air infiltration model developed at Lawrence Berkeley Laboratory uses a limited number of building and site parameters to predict the infiltration of residential structures from wind speeds and temperature differences.[1,2] As with any simplified model, a primary concern is how easily the model parameters can be determined and how accurate and applicable its predictions are. Potential users and researchers would like to understand the effects of individual assumptions and have quantitative estimates of the errors induced under different circumstances. In this paper we attempt to address these issues.

The LBL infiltration model has existed for approximately three years. Validation work has been done in houses and in a mobile test structure, the Mobile Infiltration Test Unit (MITU).[3-5] Although the correlations between predicted and measured infiltration have been good, analyses to date have focused on the tracking ability of the model and its dependence on the time-step considered. Furthermore, the analyses treated the model globally, not attempting to isolate the causes of discrepancy. Here, we use a larger data set to analyze the sources of error within the model. Four simplifying assumptions upon which the model is based were tested using measured data and computer simulations that isolate the potential sources of error.

INFILTRATION MODEL

The infiltration model, represented schematically in figure 1, has as its conceptual basis (1) the resistance of the building envelope to infiltration and (2) the forces that drive infiltration. The resistance of the building is characterized by a leakage area and two distribution parameters; the forces that drive infiltration are pressure differences across the building envelope caused by wind and by indoor-outdoor temperature differences. The model is described in detail elsewhere,[1,2] here we discuss only those aspects of the model that pertain to the assumptions under consideration.

ASSUMPTIONS

We will examine four of the simplifying assumptions in the LBL infiltration model: 1) the orifice-flow assumption, 2) the superposition assumption, 3) the aspect-ratio assumption, and 4) the wind-direction assumption.

Orifice Flow

To quantify the overall resistance of a building to infiltration, the model uses a single parameter, the effective leakage area. The definition of effective leakage area characterizes the airflow as orifice or square-root flow:

$$Q = L \sqrt{\frac{2}{\rho} \Delta P} \qquad (1)$$

where

Q is the airflow [m^3/s],

ΔP is the pressure drop across the building envelope [Pa],

L is the effective leakage area [m^2], and

ρ is the density of air [kg/m^3].

This assumption implies that the airflow resistance of the apertures is dominated by entrance and exit losses (orifice flow) as opposed to the viscous losses that characterize laminar pipe flow.

This flow model was developed in conjunction with a technique to measure the flow resistance of buildings, the fan pressurization technique.[6-9] Fan pressurization allows the airflow through a building envelope to be measured at several indoor-outdoor pressure differences between 10 and 60 Pa. The pressurization results can be represented by an empirical relationship:

$$Q = L \sqrt{\frac{2\Delta P_r}{\rho}} \left[\frac{\Delta P}{\Delta P_r}\right]^n \qquad (2)$$

where

Q is the volume flow rate of the fan [m^3/s],

L is the effective leakage area [m^2],

ΔP is the pressure drop across the leak [Pa],

ΔP_r is a reference pressure [Pa], and

n is an exponent in the range $0.5 < n < 1.0$.

The flow exponent in equation 2 has been determined for houses throughout the country to be between 0.5 and 0.75.

Although the pressurization results seem to contradict our assumption of square-root flow (i.e., n = 0.5), this assumption reduces complexity; furthermore, effective leakage area has a direct physical interpretation. Because the pressures driving infiltration are normally within a limited range (1 to 10 Pa), and because calculating the flow resistance near the middle of this range minimizes the error from the assumption of square-root flow, we use ΔP_r = 4 Pa as our reference.

The effective leakage area and exponent can be determined from the pressure-flow data by fitting the pressurization data to equation 2. By assuming orifice-flow, the LBL model does not use the measured exponent explicitly, but rather uses the flow rate at 4 Pa to calculate the effective leakage area, assuming the exponent to be equal to one-half.

Superposition

In the above discussion we define the resistance of a building to airflow caused by a uniform pressure drop across the building shell. In the case of naturally-induced air infiltration, there are two driving forces: wind and stack (temperature difference) effects. The airflows resulting from the two driving forces must be combined to arrive at the total infiltration of a structure. This problem could be solved exactly by a point-by-point addition of the pressures resulting from each driving force, followed by an integration of the flows through all openings. Such a procedure is too detailed to be practical for a simplified model. If the expressions for wind- and stack-induced infiltration are interpreted as effective pressure drops across the leakage area of the structure, the total infiltration rate can be determined by adding these pressures. Substituting this pressure drop into the flow model (equation 1) yields the quadrature form of superposition used in the LBL model:

$$Q = \sqrt{Q_s^2 + Q_w^2} \tag{3}$$

where

Q is the total infiltration [m^3/s],

Q_s is the stack-induced infiltration [m^3/s], and

Q_w is the wind-induced infiltration [m^3/s].

The stack- and wind-induced flows can be related to the weather and leakage variables as follows:

$$Q_s = L\, f_s \sqrt{\Delta T} \tag{4}$$

$$Q_w = L\, f_w\, v$$

where

f_s is the stack parameter $[m/s/K^{1/2}]$,
ΔT is the inside-outside temperature difference [K],
f_w is the wind parameter [dimensionless], and
v is the wind speed [m/s].

The assumption of superposition combines the (independently calculated) stack and wind flows using quadrature (equation 3).

Aspect Ratio

In calculating the wind effect for the LBL model, we used a set of wind-pressure coefficients derived from wind-tunnel studies of rectangular structures.[10] Three sets of coefficients were given, one for each aspect (length-to-width) ratio. In the interest of simplification, we averaged the results from all three sets; for an exact treatment, of course, we would use only the set of coefficients that corresponds to the aspect ratio of the building in question. The aspect-ratio assumption, then, is that the infiltration rate of any structure can be determined using wind-induced infiltration averaged over aspect ratio.

Wind Direction

The wind-pressure coefficients mentioned above depend on direction as well as aspect ratio. In calculating wind effect in the LBL model, the directional dependence is averaged out. This simplification assumes that all directions are equally represented for each infiltration prediction, and implicitly assumes that the shielding around the structure is independent of direction. In other words, the wind-direction assumption eliminates the directional dependence of the wind-induced-infiltration predictions.

FIELD MEASUREMENTS

To probe the effect of the four assumptions on the model, we need a detailed long-term database with which to test our hypotheses. This need for data is filled by MITU.[11]

MITU, illustrated in figure 2, is a construction-site office trailer that was modified and instrumented for infiltration research. Because it allows control of building and site parameters, it is useful for performing extended field studies in a variety of climates. MITU is a wood-frame structure 4.9 m long, 2.4 m wide, and 2.4 m high. The walls and floor of the trailer contain a total of sixteen window openings that can be fitted with interchangeable, calibrated leakage panels. The leakage areas of the panels and the trailer shell are determined with a fan pressurization system designed to fit into a window opening and measure airflow using an orifice plate. Air infiltration is monitored with the Continuous Infiltration Monitoring System (CIMS)[11], and on-site wind speed and temperatures are continuously recorded.

During the winters of 1981 and 1982, the MITU trailer was stationed in Reno, Nevada, at two sites selected for their cold temperatures and uniform wind exposure. The first winter was spent in a sparsely populated residential area on the outskirts of town, the second winter on an exposed site at the Reno airport. Each of the two data sets consists of about 800 measurements of half-hour average wind speeds, wind directions, temperature differences, and infiltration. In both, the leakage distribution in the trailer was uniform, the only difference being that there was a leakage panel in the floor in 1981 and none in 1982.

We began our analysis by comparing the overall accuracy of the LBL model for the two sets of measured data. Table 1 presents the mean and the standard deviation of the measured infiltration versus predicted infiltration. In addition we present the mean and standard deviation of the error (i.e., the difference between the model predictions and the measured data).

TABLE 1

Measured Infiltration vs LBL Model Predictions [m^3/h]

Data Set	1981	1982	Total
Mean of Measurements	40.4	45.4	42.7
Standard Deviation of Measurements	31.3 (77%)	40.9 (90%)	36.1 (85%)
Mean of Predictions	45.1	49.1	46.8
Standard Deviation of Predictions	24.0	31.8	27.8
Mean of Errors	4.7 (12%)	3.7 (8%)	4.1 (10%)
Standard Deviation of Errors	10.0 (25%)	13.5 (30%)	11.8 (28%)

Note: All percentages are relative to the mean measured infiltration.

The mean error is a measure of the <u>bias</u> of the model; that is, how far an average prediction will be from the true value (as given by the measured value). The standard deviation of the errors is a measure of the <u>scatter</u> of the model, or the range of error over which an individual prediction will vary.

The smaller the bias, the better the long-term average prediction; thus, if only seasonal averages are desired, the only criterion for choosing a model would be its bias. The scatter, on the other hand, is a measure of how well the model follows short-term changes; the smaller the scatter, the better the model can track changes in infiltration. A model that has very little bias may have very large scatter, or vice versa. An example of a model with large scatter is one that assumes infiltration to be independent of weather. In this case, a single best infiltration rate would be found and the scatter would be equal to the standard deviation of the measurements -- in this case 85%, or more than three times the scatter of the LBL model (28%). These two values, bias and scatter, characterize the accuracy of a model.

The remainder of this analysis explores potential sources of error within the model. It focuses on the four simplifying assumptions by attempting to correlate the errors with parameters that isolate the effects of each assumption.

Isolation of the Orifice-Flow Assumption

To isolate the effect of the orifice-flow assumption, we make use of the fact that, in general, large infiltration implies large pressures and small infiltration implies small pressures across the leaks. Because the effect of the orifice-flow assumption will change as a function of pressure, we expect it to change as a function of infiltration. The prediction errors are plotted against measured infiltration rates in figure 3. The measured data were put into bins of equal infiltration, and predictions were made for the data points in each bin. The average error in the predictions, as well as the standard deviation of that error, are plotted against measured infiltration rate. This plot demonstrates that the error has a clear-cut dependence on the measured infiltration rate and hence on the applied pressure.

The trend in figure 3 suggests that we could improve the model by correcting the orifice-flow assumption and using another flow exponent. Hypothesizing the error to be due to the assumed flow exponent of 0.5 (i.e., orifice flow), we fit the data to a power law of the form:

$$Q_m = a(Q_p)^b \tag{5}$$

$$n = 0.5\ b$$

where

Q_m is the measured infiltration rate,
Q_p is the predicted infiltration rate,
a,b are constants, and
n is the flow exponent.

To first order, the infiltration rate varies with the effective pressure drop across the flow resistance of the house. Thus, the constant b can be used to determine the actual flow exponent of the leakage. Substituting the assumed square-root dependence of the predicted infiltration and an unknown flow exponent for the measured infiltration, the constant b is equal to twice the unknown flow exponent. The results of these fits on both data sets are displayed in table 2.

TABLE 2 Results of Power-Law Fits				
Data Set	a	b	n	R^2
MITU 1981	0.243	1.33	0.66	0.91
MITU 1982	0.327	1.25	0.63	0.91

The flow exponent of the MITU leakage panels was measured as 0.62, which is consistent with the the apparent flow exponents of 0.66 and 0.63 shown in table 2. These comparisons show that the error caused by the assumption of square-root flow is measurable and may be significant.

Isolation of the Superposition Assumption

Our assumption of quadrature superposition has no effect on the predictions whenever either stack or wind effects dominate; thus, we would expect to see an error from this assumption only when the two effects are of comparable size. Accordingly, we can isolate this effect by plotting the error in predictions against the ratio of stack-induced infiltration to wind-induced infiltration, as shown in figure 4. The results show that this superposition technique overpredicts the total infiltration when the magnitudes of the two infiltration rates are comparable (i.e., when the ratio is close to 1). Although the curve approaches zero for both stack-dominated (high ratio) and wind-dominated (low ratio) regimes, it is not symmetric. The same asymmetry is found in both data sets.

Isolation of the Aspect Ratio Assumption

Because it is not possible to physically alter the aspect ratio of MITU, we cannot directly isolate the effect of the aspect-ratio assumption. The asymmetry of figure 4 indicates that the wind-dominated regime differs from the stack-dominated regime, and we expect that the aspect-ratio assumption can affect the infiltration only in the wind-dominated regime. An examination of measured infiltration vs stack/wind ratio (figure 5), however, suggests another possible interpretation. The average measured infiltration rate decreases significantly with increasing stack/wind ratio. This bias in the data has the effect adding the error from the flow model exponent (see above) to the other errors. For this reason, no definitive conclusions can be reached from measured data regarding the aspect-ratio assumption.

Isolation of the Wind Direction Assumption

To isolate the effect of the wind-direction assumption, we plot the error as a function of incident wind direction (see figure 6). Although the error bars for both data sets are quite large, the two curves seem to exhibit the expected 180^{o} rotational symmetry. There are two effects that the wind-direction assumption hides. The first is the change in infiltration with wind direction due to the geometry of the house. If the house were cylindrical, this effect would not exist, but the rectangular shape, as well any additional corners found with more irregular geometries, perturb the flow around and into the house. The second effect is that of nonuniform local shielding (trees, other houses, etc.), which is quite difficult to quantify or predict. For this experiment, however, the shielding was uniform and therefore does not enter into the analysis.

COMPUTER-SIMULATED INFILTRATION IN MITU

In the previous sections, we compared measured infiltration with that predicted by the LBL model and attempted to isolate the effects of the four assumptions by plotting the error against different quantities (i.e., infiltration, stack/wind ratio, wind direction). Although this procedure gives a qualitative understanding of the effects, it cannot yield quantitative results. To produce quantitative results we must be able to separate the effects of each assumption. By constructing a simulation in which the various assumptions used in the LBL model can be individually removed, we can probe the effects each assumption has on the results obtained with the model.

Before discussing how each assumption is removed and what effect each has on the bias and scatter, we examine the accuracy of the full simulation (i.e., with all four assumptions removed). If the full simulation substantially reduces bias and scatter, then we can use it in place of measurements to probe the effects of each assumption. These predictions were compared with the measured data in the same manner as were the LBL infiltration model predictions. Table 3 presents the results of this comparison for the full simulation as table 1 did for the LBL model.

TABLE 3
Measured Infiltration vs Full Simulation [m^3/h]

Data Set	1981	1982	Total
Mean of Measurements	40.4	45.4	42.7
Standard Deviation of Measurements	31.3 (77%)	40.9 (90%)	36.1 (85%)
Mean of Errors (LBL Model)	4.7 (12%)	3.7 (8%)	4.1 (10%)
Standard Deviation of Errors (LBL Model)	10.0 (25%)	13.5 (30%)	11.8 (28%)
Mean of Simulation	36.1	41.3	38.4
Standard Deviation of Simulation	25.6	39.5	32.7
Mean of Errors (Simulation)	-4.3 (-11%)	-4.1 (-9%)	-4.3 (-10%)
Standard Deviation of Errors (Simulation)	8.3 (21%)	10.1 (22%)	9.2 (22%)

Note: The first four rows in this table are reproduced from table 1.
Note: The last two rows are the errors in the simulation relative to the measured infiltration.

As indicated by the decrease in the standard deviation of the error (from 28% to 22% for the entire data set), the simulation tracks fluctuations in infiltration better than the LBL model. (Note that the standard deviation would not be zero even if the model were perfect, because the error also includes random errors in the measurements -- infiltration, wind, temperature, etc.-- which we estimate to be about 15%.) Although the LBL model overpredicts and the simulation underpredicts, these errors in mean infiltration are within the range of accuracy of our measurements. The simulation can thus be used to probe the effects of individual assumptions in detail, by selectively reinstating the simplifying assumptions used in the LBL model.

Effect of the Orifice-Flow Assumption

To calculate flows, the LBL model uses a flow equation of the form of equation 1. The simulation uses a flow equation of the form of equation 2, where the exponent, n, is set to 0.65, thereby removing the orifice-flow assumption. In this way, the flow calculated in the simulation uses the proper exponent.

Figure 3 showed that the errors in the LBL model were a function of pressure drop (infiltration), which we attributed to the orifice-flow assumption. If the simulation corrects this assumption, we expect this trend to disappear. In figure 7, which plots the full simulation results vs measured infiltration, we find that the previous correlation of error with infiltration rate seems to have disappeared, suggesting that the flow exponent problem has been corrected.

To quantify the effect of the orifice-flow assumption, we compare the full simulation to a simulation with the orifice-flow assumption. Because all other aspects are identical, this comparison focuses on only this assumption. Table 5 displays the bias and scatter associated with the orifice flow assumption, calculated from the weather data taken with MITU.

TABLE 5

Effect of Orifice Flow Assumption [m^3/h]

Data Set	1981	1982	Total
Bias	3.8 (9%)	2.4 (6%)	3.1 (8%)
Scatter	7.3 (18%)	9.4 (23%)	8.3 (20%)

Note: The percentages are relative to the mean infiltration calculated using the full simulation.

Effect of the Superposition Assumption

The superposition assumption allows the wind and stack effects to be calculated independently and then combined. The general form of the superposition assumption is as follows:

$$Q = \left[Q_s^{1/n} + Q_w^{1/n} \right]^n \tag{6}$$

In the LBL model the exponent is always 1/2, reducing the above equation to the quadrature form discussed earlier. In the simulation the exponent may or may not be 1/2 and so the more general form is used.

In the simulation, equation 6 is used for the superposition assumption. When the assumption is removed, the pressures are calculated on a point-by-point basis (using the same wind-tunnel coefficients and stack parameters as in the LBL model), and then integrated. This integration uses an iterative procedure to determine the interior pressure by satisfying continuity. As with the orifice-flow assumption, the effect of this assumption can be seen by comparing the full simulation to the simulation with the superposition assumption (see table 6).

TABLE 6

Effect of Superposition Assumption [m^3/h]

Data Set	1981	1982	Total
Bias	5.2 (13%)	4.5 (11%)	4.8 (12%)
Scatter	2.2 (5%)	2.3 (6%)	2.3 (6%)

Note: The percentages are relative to the mean infiltration calculated using the full simulation.

Effect of the Aspect Ratio Assumption

When the aspect-ratio assumption is used (as in the LBL model), the infiltration (wind-induced portion) is calculated for each of the three aspect ratios and then averaged. When the aspect-ratio assumption is not used (as in the full simulation), the correct (2:1 for MITU) aspect ratio is used. Although the size and direction of this effect will change for different structures, the 2:1 aspect ratio results are exact for MITU. The effect of averaging over aspect ratio is determined by comparing the full simulation to the simulation that uses the aspect-ratio assumption. Table 7 displays the results of this comparison.

TABLE 7

Effect of Aspect Ratio Assumption [m^3/h]

Data Set	1981	1982	Total
Bias	4.0 (10%)	4.7 (11%)	4.3 (11%)
Scatter	5.1 (13%)	6.4 (15%)	5.7 (14%)

Note: The percentages are relative to the mean infiltration calculated using the full simulation.

Because structures with 1:1 or 4:1 aspect ratios are further from the average value, the error resulting from averaging over aspect ratio will be larger.

Comparison of the LBL Model with Direction-Independent Simulations

The three previous comparisons have shown the effect of each assumption relative to a full simulation. Almost all these assumptions interact with one another. To show this effect qualitatively, we have produced three plots (figures 8-10) that compare the LBL model to simulations that use various sets of assumptions.

Figure 8 focuses on the effect of the flow exponent and the effect of aspect ratios. Predictions were made with the correct and averaged aspect ratios, using both 0.5 and 0.65 as flow exponents. The differences between LBL model predictions and those made with the simulations are plotted against the LBL-predicted infiltration rate. The effect of using an average aspect ratio is represented by the solid horizontal line. This line was determined for wind-dominated infiltration, representing an upper bound for the error (in MITU). As the stack/wind ratio increases, the wind-induced infiltration has less influence, decreasing the percentage error. The dashed and dotted curves are made with 0.65 as the flow exponent, using the MITU and the average aspect ratio. The overprediction resulting from the average aspect ratio translates into an offset of the difference curve, with very little effect on its shape. As with a flow exponent of 0.5, the curve for the average aspect ratio will approach the curve for the MITU ratio as the stack/wind ratio increases.

Figure 9 shows the effects of the flow superposition technique and aspect ratio averaging. Simulation predictions were made using 0.5 as the flow exponent and were averaged over all wind directions. The effect of averaging over aspect ratio as a function of stack/wind ratio is shown by the solid line. The dotted curve isolates the effect of the superposition technique. Unlike the error resulting from using a 0.5 flow exponent, this error is always positive; that is, the model always overpredicts the infiltration rate. The overpredictions resulting from superposition and aspect ratio averaging add, resulting in the dashed line.

Figure 10 compares LBL model predictions with the best wind-independent simulation predictions (i.e., only the wind-direction assumption is used). The three curves at different stack/wind ratios have the same shape but differ in their zero crossings. As expected, overprediction dominates for a stack/wind ratio of unity (dashed curve). Comparing the solid curve with the dotted-dashed curve illustrates the effect of averaging over aspect ratio.

Effect of the Wind Direction Assumption

When the wind-direction assumption is used (as in the LBL model), the wind effect is calculated by averaging wind effects for all directions. When this assumption is not used (as in the full simulation), the wind effect is calculated for each direction using the appropriate wind pressure coefficients. As for the other three assumptions, we compare the full simulation to the simulation that uses this assumption:

TABLE 8

Effect of Wind Direction Assumption (m^3/h)

Data Set	1981	1982	Total
Bias	0.7 (2%)	-0.3 (-1%)	0.2 (0%)
Scatter	7.1 (18%)	8.6 (21%)	7.8 (19%)

Note: The percentages are relative to the mean infiltration calculated from the full simulation.

The three figures discussed in the previous section summarize the effects of the three assumptions that are independent of wind direction. Figure 11 shows the error caused by the wind-direction assumption in conjunction with the superposition assumption. The error in prediction is the difference between using and not using the wind-direction assumption. Note that the superposition assumption increases the error resulting from averaging over wind direction. The dashed curve should be compared with the plot of measured errors versus wind direction (figure 6).

CONCLUSIONS

We have examined the four major assumptions upon which the LBL infiltration model is based: orifice flow, superposition of flows, aspect ratio averaging, and wind direction averaging. Comparisons with measured data helped to isolate these assumptions, and a simulation using a detailed computer model gave estimates of the bias and scatter due to these effects. The table below summarizes our quantitative results:

TABLE 9

Summary of Assumption Accuracies

Assumption	Bias [%]	Scatter [%]
Orifice Flow	8	20
Superposition	12	6
Aspect Ratio	11	14
Wind Direction	0	19
LBL Model	22	23

The total bias and scatter associated with each assumption, supports the following conclusions. The 8% bias for the orifice-flow assumption is a relatively small overprediction; the 20% scatter, however, demonstrates that this assumption has a much larger effect on the ability of the model to track infiltration than on the its ability to find mean values.

For the orifice-flow assumption, the bias was smaller than the scatter, whereas the superposition assumption shows the opposite trend. This behavior indicates that the superposition assumption, which is only operative when the stack/wind ratio is near unity, causes an overprediction of 12% but increases the scatter of the model only slightly (6%). Thus, the superposition assumption primarily affects the mean value of the predictions rather than the ability of the model to track infiltration.

The aspect-ratio assumption is operative only when the wind-induced infiltration is significant. For our data set we find that both the bias (11%) and the scatter (14%) are significant sources of error. The wind direction effect is also operative only when the wind-induced infiltration is significant, but it shows markedly different behavior. The bias due to the wind direction assumption is virtually zero, indicating that this assumption has no effect on the ability of the model to predict average values. The scatter(19%), however, is as large as for any of the other assumptions, indicating that wind direction is extremely important to the ability of the model to track infiltration.

Each assumption has a distinct effect on the accuracy of the LBL model. Because all the assumptions interact, however, we cannot simply add the biases or scatters to find the overall effect of the four assumptions. To estimate this total effect, we made a direct comparison of the full simulation and the LBL model (last row of table 9) and found that the bias is 22% and the scatter 23%. The mean error is consistent with the 10% LBL overprediction and the -10% simulation underprediction compared to measured data. The discrepancy between this error and the LBL prediction vs measured error is due to factors other than those considered herein; the difference, however, is less than the estimated 15% measurement error and does not change the interpretation of these results. To the extent that these four assumptions are the most significant and that these data are typical, the 22% bias and 23% scatter quantify the accuracy of the LBL infiltration model.

Although table 9 summarizes the numerical effects of the different assumptions, it may also be important, in certain circumstances, to be aware of the trends. Some of these trends are apparent in figures 8 through 11. As can be seen in figures 3 and 8, the assumption of orifice flow causes overprediction for low infiltration rates and underprediction for high rates (high and low infiltration are relative to flow induced by an effective pressure equal to the reference pressure, 4 Pa). In other words, if a particular application of the LBL model is primarily in one regime or the other, there can be systematic overprediction or underprediction. Similarly, the assumption of superposition causes systematic overprediction whenever the stack/wind ratio is near unity. Figures 4 and 9 demonstrate this behavior.

The trend associated with aspect ratio is not as clear. Figures 8 through 10 demonstrate that aspect ratio causes an overprediction in wind-dominated cases. For a building having a different aspect ratio, however, aspect ratio averaging may cause either underprediction or overprediction. The wind direction assumption also affects the wind-induced infiltration. Figures 6 and 11 show that the variation for different directions may be quite large even though the average effect may be small. Thus, if in a particular instance the wind direction is very steady, a significant error may be induced by averaging the infiltration from all wind directions.

For this data set, which consists of about 1600 half-hour measurements, the LBL model predictions averaged 10% too high and have a scatter around that value of 28%. In some research projects a great deal of accuracy might be needed in predicting infiltration; however, for most uses, the 10% mean overprediction caused by the LBL model is acceptable. Furthermore, the ability of the model to track the short-term behavior with a scatter of only 28% is quite good.

FUTURE WORK

The quantitative results we have presented indicate the effect each assumption has on the accuracy of the LBL model for the data set we have considered. We have analyzed only a particular structure in one climate zone, and cannot assume these results apply to all cases. For these conclusions to be generalizable to other structures and climates, this study should be repeated. We expect our results to remain essentially unchanged.

If we treat these conclusions as general, correcting for the most obvious trends becomes an open research topic. For example, the overprediction at low infiltration rates and the underprediction at high infiltration rates caused by the orifice-flow assumption might be mitigated by developing a scaling law that makes use of the exponent as measured from fan pressurization. The systematic overprediction for stack/wind ratios near unity could be alleviated by developing a correction factor as a function of this ratio. Because the aspect ratio and wind direction assumptions affect only the calculation of the wind effect, it may be feasible to develop a slightly more accurate form for the wind-induced infiltration, one that incorporates wind direction and building aspect ratio.

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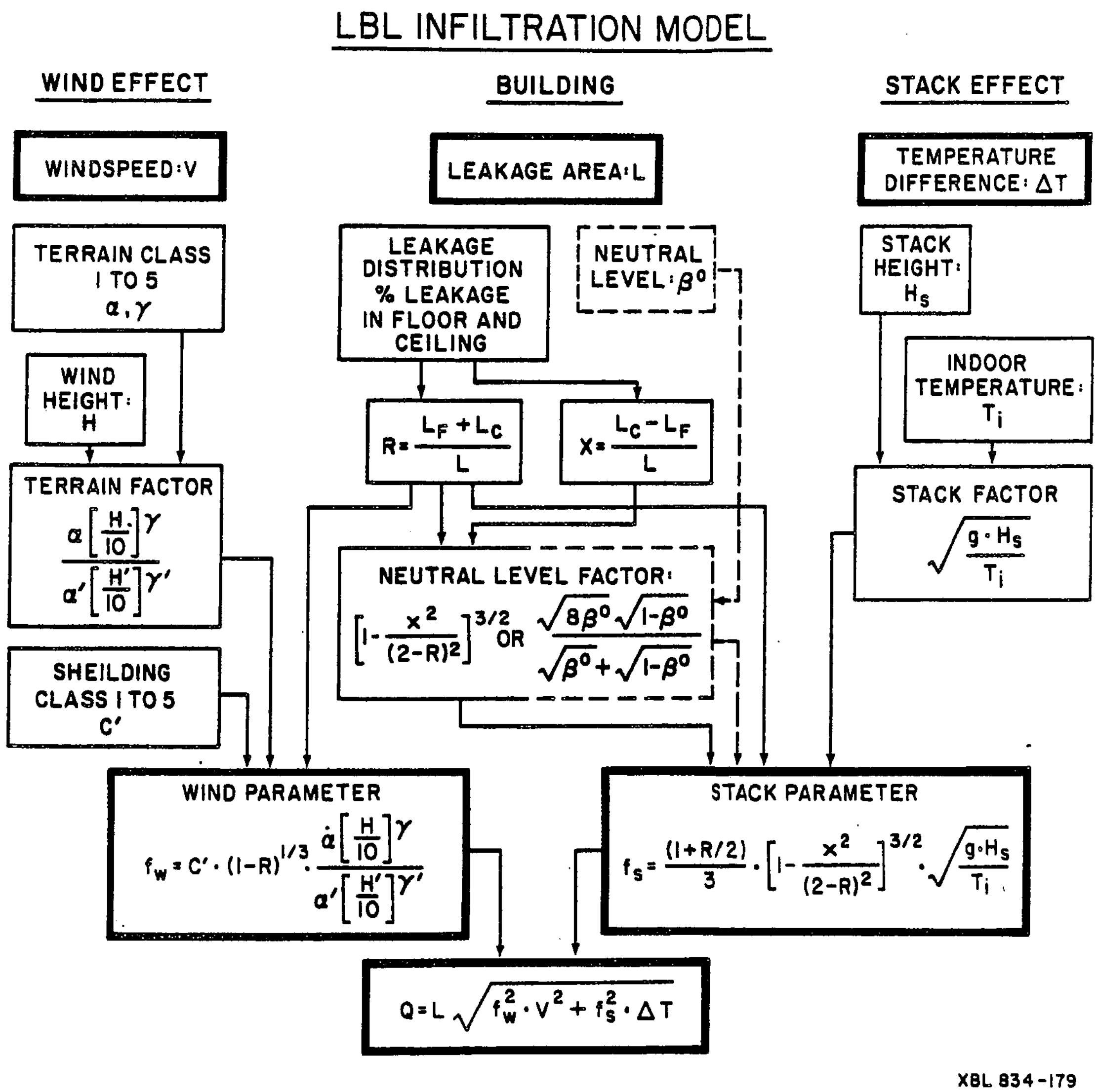

Figure 1: Schematic representation of LBL infiltration model.

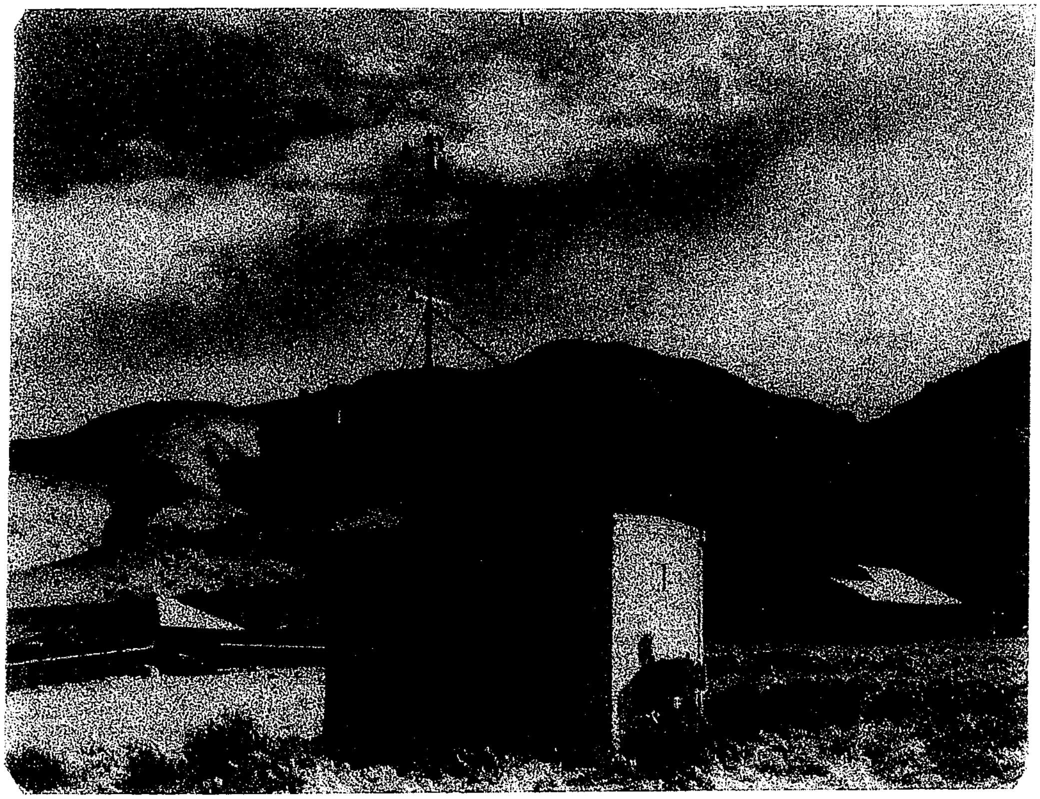

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Figure 2: Mobile Infiltration Test Unit at Reno, Nevada test site in 1981.

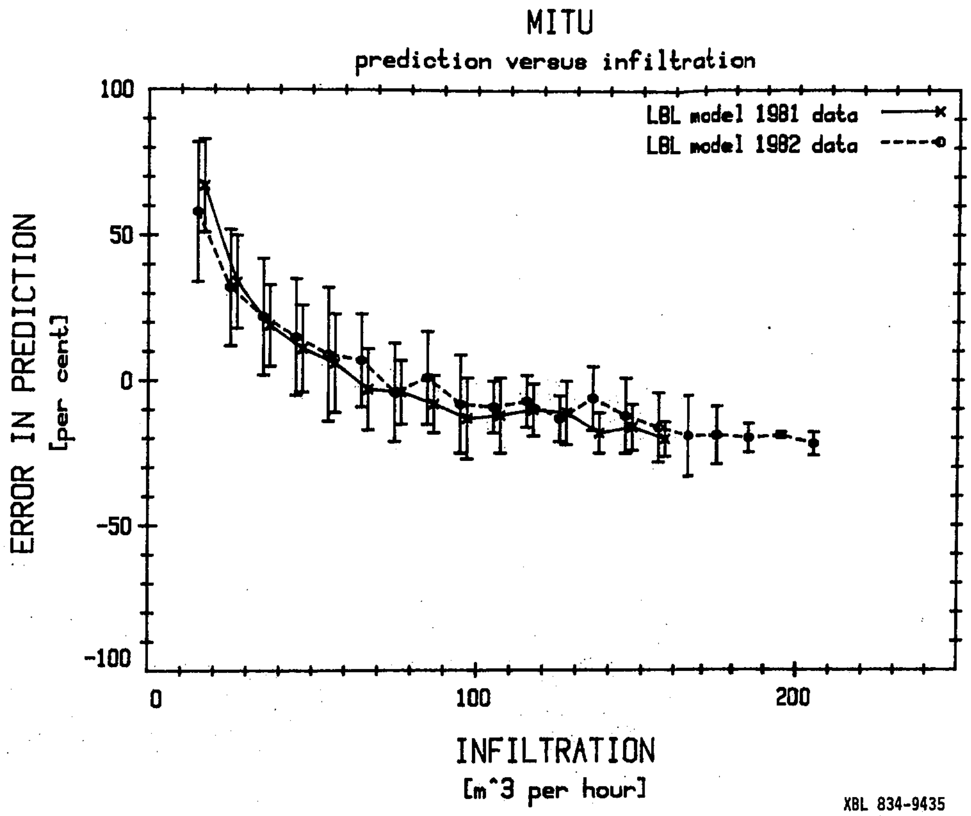

Figure 3: Error in LBL infiltration model predictions versus measured infiltration rate of MITU, including standard deviations.

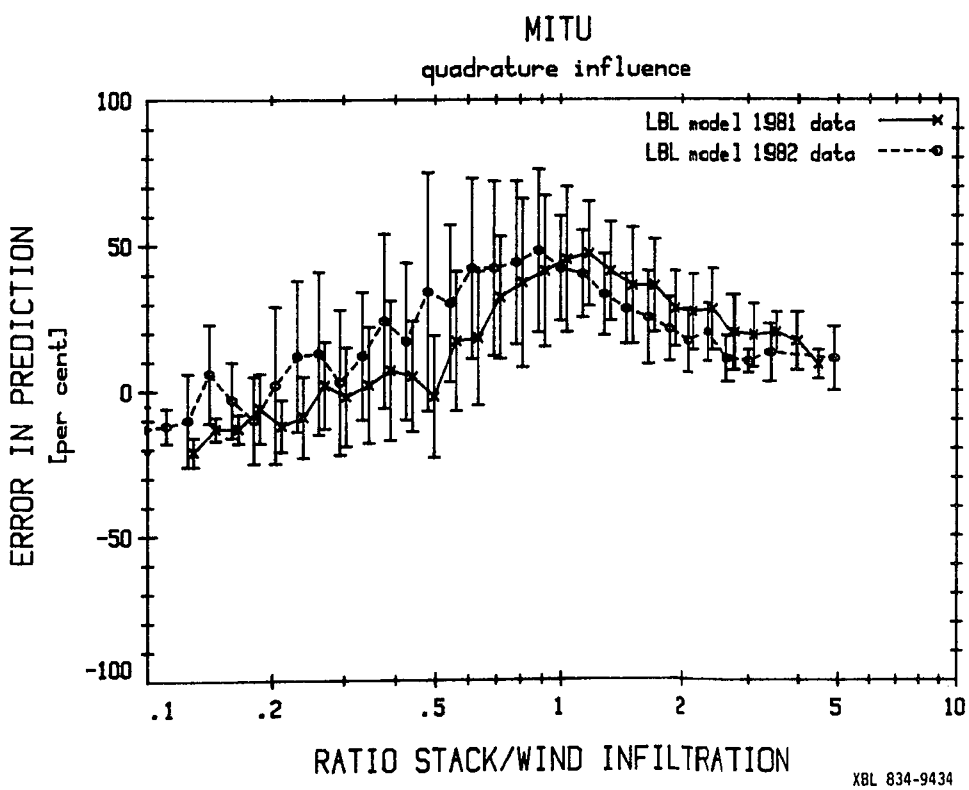

Figure 4: Error in LBL infiltration model predictions versus ratio of stack-induced to wind-induced infiltration predictions, including standard deviations.

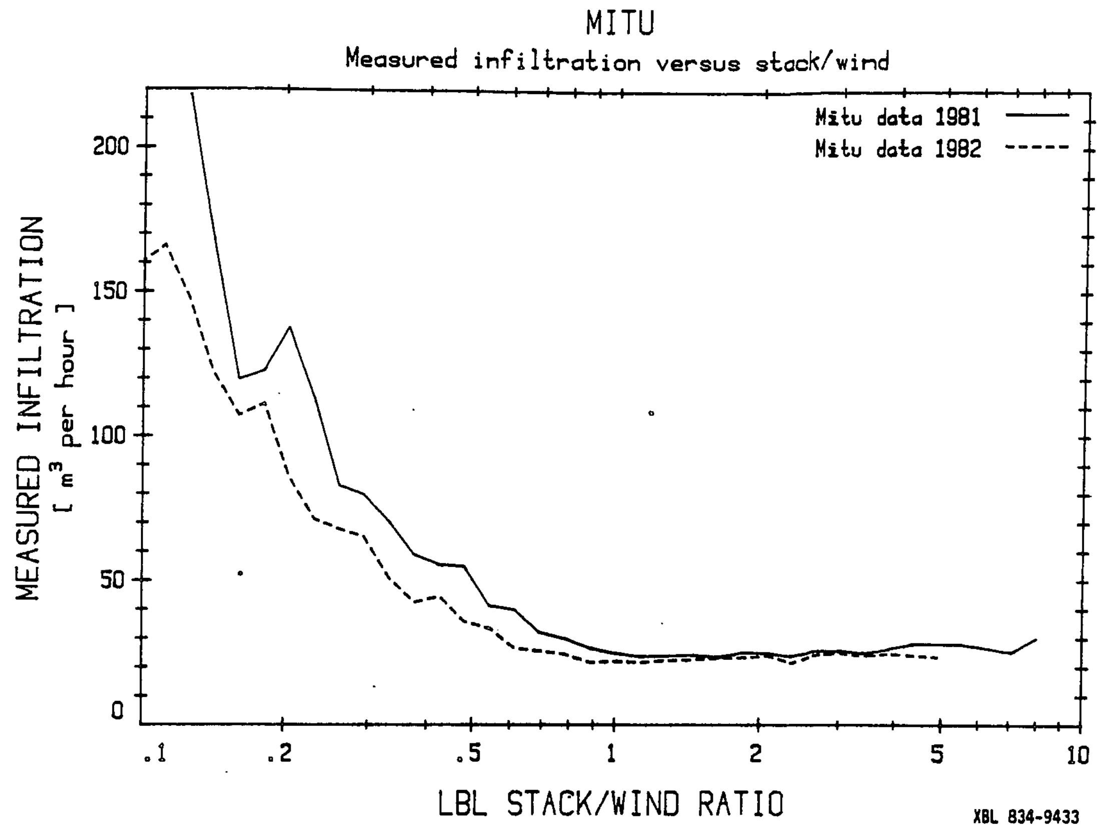

Figure 5: Measured infiltration rates versus ratio of stack-induced to wind-induced infiltration predictions.

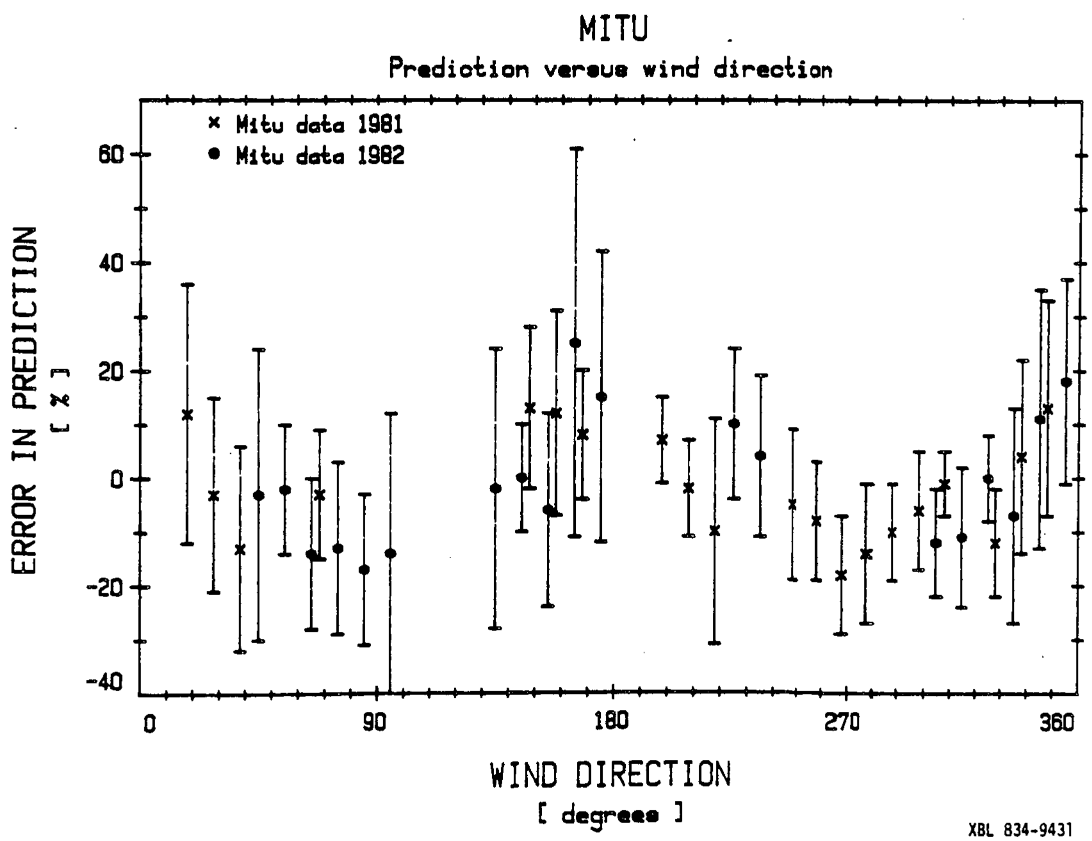

Figure 6: Error in LBL infiltration model predictions versus wind direction (for windspeeds > 3 m/s), including standard deviations.

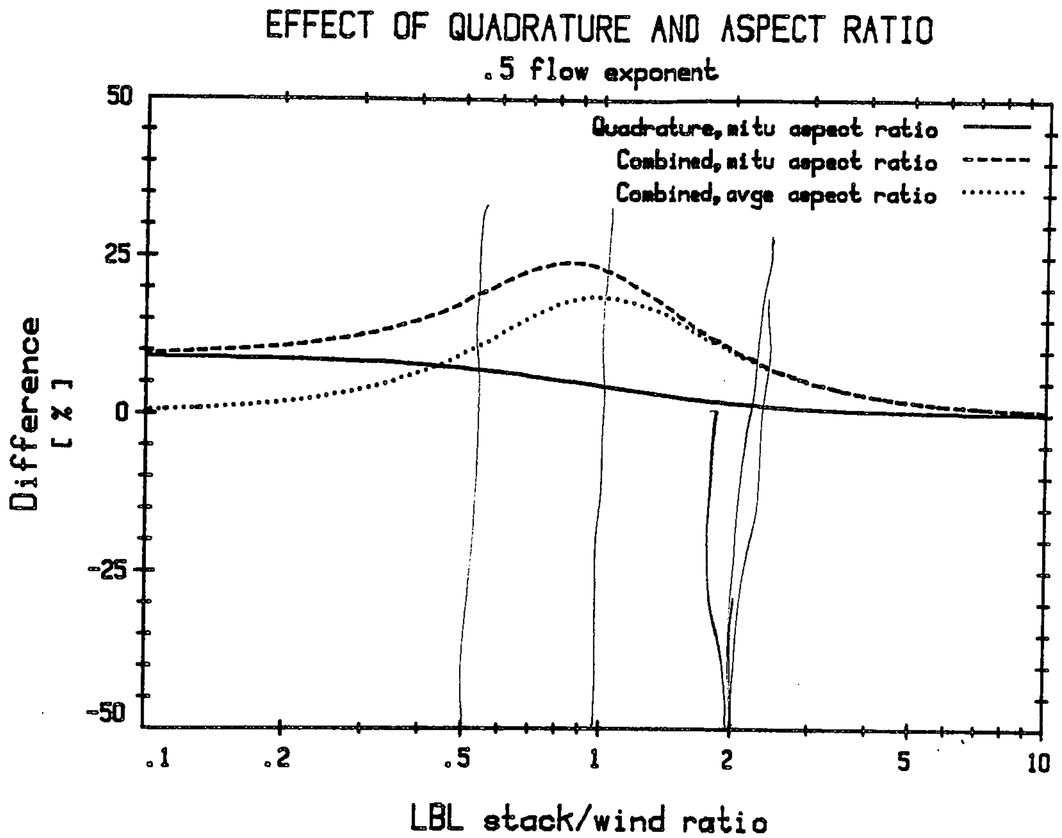

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Figure 9: Difference between LBL model predictions and detailed simulation predictions made by integrating the combined wind and stack pressures versus LBL stack-wind ratio.

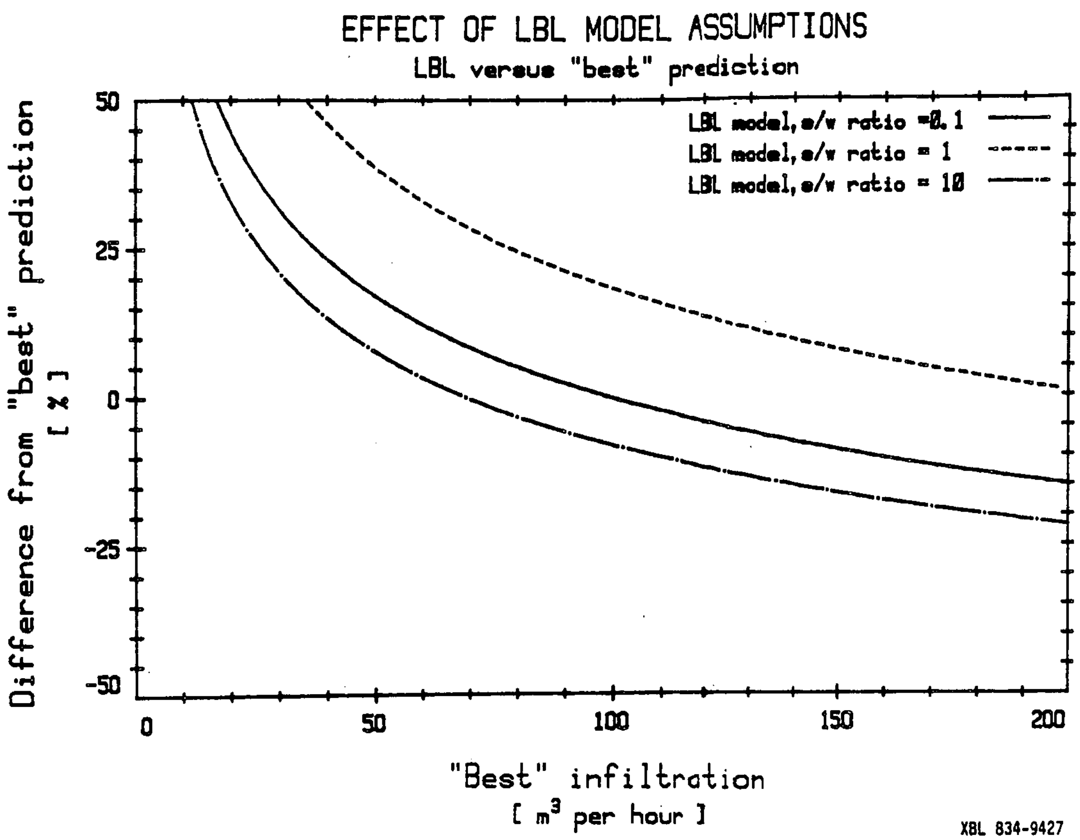

Figure 10: Difference between LBL model predictions and "best" infiltration predictions versus "best" infiltration predictions.

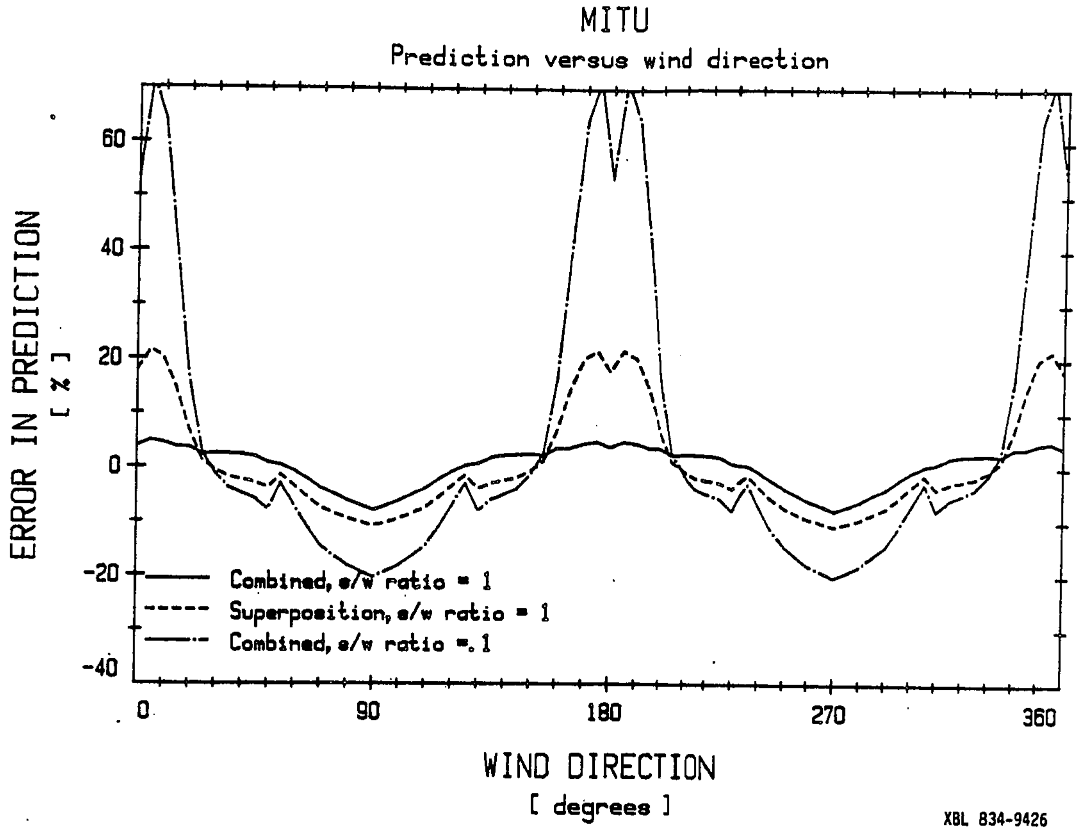

Figure 11: Difference between predictions made for each wind direction and predictions averaged over all directions versus wind direction.

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